Booster Beam Intensity Data

C.J. Gardner

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1 Polarized Protons in Booster

An upper limit on intensity at injection is 2.0×10^{12} protons per Booster cycle. The kinetic energy at injection is 200 MeV and at extraction it is 1.417 GeV. A typical repetition rate would be one Booster cycle with beam every 3.6 seconds.

During polarized proton operations it is not uncommon to scrape the beam horizontally and vertically during acceleration in order to achieve a beam with sufficiently small transverse emittance. Horizontal scraping occurs on the Dump at B6 while vertical scraping is most likely to occur in the number 1, 5, or 7 dipoles where the vertical beta function is large and the vertical aperture is small. The scraping can be rather severe with 50% or less of the beam surviving to extraction.

Consider the extreme case in which all of the beam (2.0×10^{12} protons) is scraped off at extraction energy (1.417 GeV). This amounts to a loss of 2.83 GeV-nucleons every 3.6 seconds or 2.83×10^{15} GeV-nucleons per hour. This is well below the OSL of 5.4×10^{17} GeV-nucleons per hour.

2 High Intensity Protons in Booster

We have not run with protons at high intensity in Booster since 2002. At that time Booster had run with intensities as high as 22×10^{12} protons at 1.94 GeV kinetic energy per Booster cycle with 4 cycles every 3.6 seconds. In this mode of operation the allowable loss in Booster was limited (by Operations Procedure 6.1.10.a) to 6×10^{12} protons per second at top energy.

3 Deuterons in Booster

Deuterons were last accelerated in Booster during RHIC Run 8. Beam was accelerated on 8 Booster cycles per AGS cycle with peak totals (recorded on 22 January 2008) of 20.0×10^{11}, 12.4×10^{11}, and 8.605×10^{11} deuterons per 8 Booster cycles at Booster Input, Early, and Late respectively. Here "Early" is shortly after injection and "Late" is close to extraction. The kinetic energies at injection and extraction were respectively 9.26 and 506 MeV per nucleon. Losses ranged from 30% to 40% at injection and from 20% to 30% during acceleration. The AGS repetition period was 4 seconds.

4 Gold in Booster

For delivery of gold ions to RHIC, beam is accelerated on 4 Booster cycles per AGS cycle. Here the peak Early and Late intensities are respectively 5.74×10^9 and 3.2×10^9 ions per Booster cycle. The kinetic energies at injection and extraction are 0.928 and 101 MeV per nucleon respectively. Minimum losses are 20% at injection and 30% during acceleration. The AGS repetition period was 4 seconds.

5 Ions in Booster for Delivery to NSRL

Ion intensities recorded by K. Zeno from 2004 through 2007 are listed in **Table 1**.

Table 1: Peak Ion Intensities in Booster for Delivery to NSRL

Ion	Input	Early	Late	Unit
p (Tandem)	2.5	1.2	0.8	10^{11}
pp (Linac)	4.3	3.0	2.8	10^{11}
O7+	4.6	2.0	0.94	10^{10}
Si9+	3.0	1.4	0.58	10^{10}
Si13+	2.2	1.1	0.67	10^{10}
Cl14+	9.0	4.0	2.4	10^9
Ti18+	5.4	2.4	1.3	10^9
Fe20+	9.3	4.4	3.1	10^9
Au31+	5.8	4.6	3.2	10^9

Here kinetic energy at extraction is 200 MeV per nucleon for gold ions 1000 Mev per nucleon for all the others.

6 Maximum Proton Energy and Intensity in Booster

19 June 2003:

1. Assume **one Booster cycle every three seconds** with 24×10^{12} protons accelerated per cycle to the maximum Booster magnetic rigidity of 17.0 Tm. The kinetic energy of protons at this rigidity is 4.24 GeV. This gives 1.02×10^{14} GeV-nucleons per Booster cycle. At the rate of one cycle every three seconds this gives 1.22×10^{17} GeV-nucleons per hour, which is safely below the Booster OSL of 5.4×10^{17} GeV-nucleons/hour.

2. Assume **one Booster cycle every two seconds** with 24×10^{12} protons accelerated per cycle to the maximum D6 septum magnetic rigidity of 13.0 Tm. The kinetic energy of protons at this rigidity is 3.07 GeV. This gives 7.37×10^{13} GeV-nucleons per Booster cycle. At the rate of one cycle every two seconds this gives 1.33×10^{17} GeV-nucleons per hour, which is also safely below the Booster OSL.

3. Assume 7.5 **Booster cycles per second** with 24×10^{12} protons accelerated per cycle to a kinetic energy of 2 GeV. This gives 4.8×10^{13} GeV-nucleons per Booster cycle. At 7.5 cycles per second this gives 1.3×10^{18} GeV-nucleons per hour, which is well above the Booster OSL.

Case 2 gives a conservative upper limit on what could be extracted to NSRL.

7 Loss on Booster Extraction Septum at F6

29 January 2001:

C-A OPM 2.5 states that no more than 2.2×10^{19} protons/year at 1.5 GeV kinetic energy (or equivalent) may be stopped at the Booster F6 extraction

septum. At 2.0 GeV kinetic energy the limit would be 1.65×10^{19} protons/year.

The loss rate at the septum may be as high as 6×10^{12} protons/second during high-intensity proton operations. This amounts to 5.18×10^{17} protons per day (24 hours) and 3.63×10^{18} protons per week (168 hours). At this loss rate, the limit of 1.65×10^{19} protons would be reached in 32 days.

Ed Lessard reports that TLDs deployed in the area where BAF is now under construction accumulated a dose of some 400 mr (millirem) over the last high-intensity proton running period. This is evidently due to skyshine from Booster. Because of this, the area is now a Controlled Area and workers there must have appropriate training. To determine the source of the radiation, TLDs have been deployed on the Booster berm. In a memo to Ed Lessard dated 17 January 2001, Chuck Schaefer writes: "Booster Berm TLDs were hung yesterday; 4 around the perimeter fence line, 5 along the internal circular cable tray, and 3 in the inner high radiation area. They were all equipped with Landauer packs. I intend on changing them out monthly during the g-2 run".

8   Estimate of Deuterons per RHIC Bunch

30 September 2007:

The RHIC OSL is 1.2×10^{13} d per fill at an energy of 125 GeV per nucleon.

Typical intensity at the Booster end of the TTB line is 1.5×10^{11} d (deuterons) per Tandem pulse. Maximum is 2.0×10^{11} d per Tandem pulse.

Assume 15% lost on profile monitor inserted in TTB line to monitor intensity in the line.

Assume 15% lost in the rest of the TTB line.

Assume 50% lost at Booster injection and capture.

Assume 10% lost during Booster acceleration.

Assume 7% lost at AGS injection and capture.

Assume 2% lost during AGS acceleration.

So (AGS Output)/(Booster Input) = 41%.

Assume 8 Tandem pulses per AGS cycle; one AGS cycle every 3.6 seconds. So 2 Booster loads end up in one RHIC bunch. This gives

$2 \times 0.41 \times 1.5 \times 10^{11} = 1.23 \times 10^{11}$ d per RHIC bunch.

Maximum fraction of calendar time at store is 60%.

9 Estimate of Deuterons Delivered to the End of the TTB Line

30 September 2007:

Assume

$$n = 1.5 \times 10^{11} \tag{1}$$

deuterons per Tandem pulse at the end of the TTB line.

Assume AGS repetition period

$$P = 3.6 \tag{2}$$

seconds.

Let m be the number of Tandem pulses per AGS cycle.

Then the number of deuterons delivered to the end of the TTB line in T seconds is

$$N = mnT/P \tag{3}$$

and the number delivered in H hours is

$$N = mnkH/P \tag{4}$$

where

$$k = 3600. \tag{5}$$

Thus, for $m = 1$ we get 1.5×10^{14} deuterons per hour at the end of the TTB line; for $m = 8$ we get 1.2×10^{15} deuterons per hour.

Let E be the transport efficiency of the TTB line.

Then the number of deuterons lost in the TTB line in T seconds is

$$L = \left(\frac{1 - E}{E}\right) mnT/P \tag{6}$$

and the number lost in H hours is

$$L = \left(\frac{1 - E}{E}\right) mnkH/P. \tag{7}$$

We shall assume that

$$E = 0.85. \tag{8}$$

9.1 Tandem, Booster and AGS Setup Period

4 days with $m = 1$ and $H = 10$ gives $N = 6 \times 10^{15}$, $L = 1.06 \times 10^{15}$.

2 days with $m = 8$ and $H = 10$ gives $N = 24 \times 10^{15}$, $L = 4.24 \times 10^{15}$.

7 days with $m = 8$ and $H = 12$ gives $N = 101 \times 10^{15}$, $L = 17.8 \times 10^{15}$.

This gives a total of

$$N = 131 \times 10^{15} \tag{9}$$

deuterons delivered to the end of the TTB line, and a total of

$$L = 23 \times 10^{15} \tag{10}$$

deuterons lost in the TTB line during this period.

9.2 Collider Setup Period

4 days with $m = 8$ and $H = 12$ gives $N = 57.6 \times 10^{15}$, $L = 10.2 \times 10^{15}$.

7 days with $m = 8$ and $H = 12$ gives $N = 101 \times 10^{15}$, $L = 17.8 \times 10^{15}$.

This gives a total of

$$N = 159 \times 10^{15} \tag{11}$$

deuterons delivered to the end of the TTB line, and a total of

$$L = 28 \times 10^{15} \tag{12}$$

deuterons lost in the TTB line during this period.

9.3 Collider Intensity Ramp-Up Period

7 days with $m = 8$ and $H = 12$. This gives a total of

$$N = 101 \times 10^{15} \tag{13}$$

deuterons delivered to the end of the TTB line, and a total of

$$L = 18 \times 10^{15} \tag{14}$$

deuterons lost in the TTB line during this period.

9.4 Physics Data Taking Period

We assume that the collider has stored beams for 85 hours each week. We take the average length of a store to be 5 hours. This gives 17 stores per week. We assume that during each store, 1 hour is used to tune the injectors with deuteron beam. We assume further that 16 of the 83 non-store hours are used for tuning the injectors and the collider with deuteron beam. This gives a total of $H = 17 + 16 = 33$ hours of tuning with deuteron beam each week during the Physics data taking period. Taking $m = 8$ we then get a total of

$$N = 40 \times 10^{15} \tag{15}$$

deuterons delivered to the end of the TTB line, and a total of

$$L = 7 \times 10^{15} \tag{16}$$

deuterons lost in the TTB line each week.

The Physics data taking period is expected to last 11 weeks.

10 Proton Loss and Energy Deposition in Booster

18 January 2010:

1. A conservative upper limit on proton intensity in Booster during Polarized Proton running is $N = 1.0 \times 10^{12}$ protons per Booster cycle.

2. The maximum proton kinetic energy is 1.5 GeV.

3. The maximum energy deposition due to beam loss is then 240 Joules per Booster cycle. (1 eV is $1.602176462(63) \times 10^{-19}$ Joules.)

4. During Run 10 there may be 2 Booster cycles per AGS repetition period. This gives a maximum energy deposition of 480 Joules per repetition period.

5. The repetition period is typically 4 seconds.

6. The **average rate of energy deposition** over the AGS repetition period is then at most 120 watts.

7. The energy loss of one proton with 1.5 GeV kinetic energy in iron is

$$-\frac{dE}{dx} = 1.482 \text{ MeV per g/cm}^2. \tag{17}$$

8. The density of iron is $\rho = 7.87$ g/cm^3. This gives an energy loss of

$$-\frac{dE}{dx}\rho N = 1.87 \text{ Joules per cm} \tag{18}$$

   for $N = 1.0 \times 10^{12}$ protons at 1.5 GeV kinetic energy in iron.

9. The specific heat of iron is $c = 0.449$ J/(gK).

Imagine now a 1 cm long sliver of iron with a cross section of 0.01 cm^2.

1. Its volume is 0.01 cm^3 and its mass is 0.0787 g.

2. It takes 0.0353 Joules to raise its temperature by 1 degree K.

3. The deposited energy of 1.87 Joules will therefore raise its temperature by 53 degrees K.

4. The melting point of iron is 1538 degrees C.

The rate of loss $-dE/dx$ increases to 15.30 MeV per g/cm^2 for protons with 100 MeV kinetic energy. In this case we have

$$-\frac{dE}{dx}\rho N = 19.3 \text{ Joules per cm} \tag{19}$$

for $N = 1.0 \times 10^{12}$ protons. This energy (19.3 Joules) deposited in the same sliver of iron will raise the temperature by 547 degrees K.

These simple results suggest (perhaps naively) that proton beams incident on the Booster Dump are relatively benign for the parameters given in the above exposition.